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Global Analysis of Neutrino Data*

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In this talk I review the present status of neutrino masses and mixing and some of their implications for particle physics phenomenology.

INTRODUCTION: THE NEW MINIMAL STANDARD MODEL

The SM is based on the gauge symmetry $SU(3)_{\rm C} \times SU(2)_{\rm L} \times U(1)_{\rm Y}$ spontaneously broken to $SU(3)_{\rm C} \times U(1)_{\rm EM}$ by the the vacuum expectations value (VEV), v, of the a Higgs doublet field ϕ. The SM contains three fermion generations which reside in chiral representations of the gauge group. Right-handed fields are included for charged fermions as they are needed to build the electromagnetic and strong currents. No right-handed neutrino is included in the model since neutrinos are neutral.

In the SM, fermion masses arise from the Yukawa interactions which couple the right-handed fermion singlets to the left-handed fermion doublets and the Higgs doublet. After spontaneous electroweak symmetry breaking these interactions lead to charged fermion masses but leave the neutrinos massless. No Yukawa interaction can be written that would give a tree level mass to the neutrino because no right-handed neutrino field exists in the model.

One could think that neutrino masses could arise from loop corrections if these corrections induced effective terms $\frac{Y^{\nu}_{ij}}{v}\left(\bar{L}_{Li}\tilde{\phi}\right)\left(\tilde{\phi}^T L^C_{Lj}\right)$ where L_{Li} are the lepton doublets. This, however, cannot happen because within the SM $G^{\rm global}_{\rm SM} = U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ is an accidental global symmetry. Here $U(1)_B$ is the baryon number symmetry, and $U(1)_{e,\mu,\tau}$ are the three lepton flavor symmetries. Terms of the form above violate $G^{\rm global}_{\rm SM}$ and therefore cannot be induced by loop corrections. Furthermore, they cannot be induced by non-perturbative corrections because the $U(1)_{B-L}$ subgroup of $G^{\rm global}_{\rm SM}$ is non-anomalous.

It follows then that the SM predicts that neutrinos are *strictly* massless. Consequently, there is neither mixing nor CP violation in the leptonic sector.

We now know that this picture cannot be correct. Over several years we have accumulated important experimental evidence that neutrinos are massive particles and there is mixing in the leptonic sector:

- Solar $\nu_e' s$ convert to ν_μ or ν_τ with confidence level (CL) of more than 7σ [1, 2].
- KamLAND find that reactor $\overline{\nu}_e$ disappear over distances of about 180 km and they observe a distortion of their energy spectrum. Altogether their evidence has more than 3σ CL [3].
- The evidence of atmospheric (ATM) ν_μ disappearing is now at $> 15\sigma$, most likely converting to ν_τ [1].
- K2K observe the disappearance of accelerator ν_μ's at distance of 250 km and find a distortion of their energy spectrum with a CL of 2.5–4 σ [1, 4].
- LSND found evidence for $\overline{\nu_\mu} \to \overline{\nu_e}$. This evidence has not been confirm by any other experiment so far and it is being tested by MiniBooNE [4].

These results imply that neutrinos are massive and the Standard Model has to be extended at least to include neutrino masses. This minimal extension is what I call *The New Minimal Standard Model*.

In the New Minimal Standard Model flavour is mixed in the CC interactions of the leptons, and a leptonic mixing matrix appears analogous to the CKM matrix for the quarks. However the discussion of leptonic mixing is complicated by two factors. First the number massive neutrinos (n) is unknown, since there are no constraints on the number of right-handed, SM-singlet, neutrinos. Second, since neutrinos carry neither color nor electromagnetic charge, they could be Majorana fermions. As a consequence the number of new parameters in the model depends on the number of massive neutrino states and on whether they are Dirac or Majorana particles.

In general, if we denote the neutrino mass eigenstates by ν_i, $i = 1, 2, \ldots, n$, and the charged lepton mass eigenstates by $l_i = (e, \mu, \tau)$, in the mass basis, leptonic CC interactions are given by

$$-\mathcal{L}_{\rm CC} = \frac{g}{\sqrt{2}}\, \overline{l_{iL}}\, \gamma^\mu\, U_{ij}\, \nu_j\, W^+_\mu + \text{h.c.}. \qquad (1)$$

Here U is a $3 \times n$ matrix $U_{ij} = P_{\ell,ii}\, {V^{\ell}_{ik}}^\dagger\, V^\nu_{kj}\, (P_{\nu,jj})$ where V^ℓ (3×3) and V^ν $(n \times n)$ are the diagonalizing matrix of the charged leptons and neutrino mass ma-

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trix respectively $V^{\ell\dagger} M_\ell M_\ell^\dagger V^\ell = \mathrm{diag}(m_e^2, m_\mu^2, m_\tau^2)$ and $V^{\nu\dagger} M_\nu^\dagger M_\nu V^\nu = \mathrm{diag}(m_1^2, m_2^2, m_3^2, \ldots, m_n^2)$.

P_ℓ is a diagonal 3×3 phase matrix, that is conventionally used to reduce by three the number of phases in U. P_ν is a diagonal matrix with additional arbitrary phases (chosen to reduce the number of phases in U) only for Dirac states. For Majorana neutrinos, this matrix is simply a unit matrix, the reason being that if one rotates a Majorana neutrino by a phase, this phase will appear in its mass term which will no longer be real. Thus, the number of phases that can be absorbed by redefining the mass eigenstates depends on whether the neutrinos are Dirac or Majorana particles. In particular, if there are only three Majorana (Dirac) neutrinos, U is a 3×3 matrix analogous to the CKM matrix for the quarks but due to the Majorana (Dirac) nature of the neutrinos it depends on six (four) independent parameters: three mixing angles and three (one) phases.

A consequence of the presence of the leptonic mixing is the possibility of flavour oscillations of the neutrinos. In this symposium we had a beautiful historical introduction to neutrino oscillations by S. Bilenky and two very interesting talks on the phenomenology of oscillations in matter by A. Smirnov and on three neutrino mixing effects by E. Akhmedov. So I will only briefly summarize here the elements which are relevant for the phenomenological analysis that I will present.

Neutrino oscillations appear because a neutrino of energy E produced in a CC interaction with a charged lepton l_α can be detected via a CC interaction with a charged lepton l_β with a probability which presents an oscillatory behaviour, with oscillation lengths $L^{\rm osc}_{0,ij} = \frac{4\pi E}{\Delta m^2_{ij}}$ and amplitude that is proportional to elements in the mixing matrix. Neutrino oscillations are only sensitive to mass squared differences. Also, the Majorana phases cancel out and only the Dirac phase is observable. Experimental information on absolute neutrino masses can be obtained from Tritium β decay experiments [5] and from its effect on the cosmic microwave background radiation and large structure formation data [6]. Also if neutrinos are Majorana particles their mass and also additional phases can be determined in ν-less $\beta\beta$ decay experiments [7].

When neutrinos travel through regions of dense matter, they can undergo forward scattering with the particles in the medium. These interactions are, in general, flavour dependent and as a consequence the oscillation pattern described above is modified but it still depends only on the mass squared differences and it is independent of the Majorana phases.

The neutrino experiments described above have measured some non-vanishing $P_{\alpha\beta}$ and from these measurements we have inferred all the positive evidence that we have on the non-vanishing values of neutrino masses and mixing. In the following I will derive the allowed ranges for the mass and mixing parameters when the bulk of data is consistently combined.

ORTHODOX FITS

I denote by *Orthodox* fits those which try to explain the evidences from solar, KamLAND, ATM and K2K experiments and assume that the LSND evidence will not be confirmed by MiniBoone.

Analysis of Solar and KamLAND

In Fig. 1 I show the results from our latest analysis [8] of KamLAND $\overline{\nu}_e$ disappearance data, solar ν_e data and their combination under the hypothesis of CPT symmetry. The main new ingredient is the inclusion of the new results from KamLAND presented in ν-2004 conference in June. We have also taken into account the new gallium measurement which leads to the average value 68.1 ± 3.75 SNU. The main features of these results are:

- In the analysis of solar data, only LMA is allowed at more than 3σ and maximal mixing is rejected by the solar analysis at more than 5σ. This is so since the release of the SNO salt-data (SNOII) in Sep 2003.
- In the analysis of the new KamLAND data the 3σ region does not extend to mass values larger than $\Delta m^2_{21} = 2\times 10^{-4}$ eV^2 because for larger Δm^2_{21} values, the predicted spectral distortions are too small to fit the new KamLAND data.
- the combined analysis allows only the lowest LMA region at 3σ with best-fit point and 1σ ranges:

$$\Delta m^2 = \left[8.2^{+0.3}_{-0.3}\right]\times 10^{-5}\ \mathrm{eV}^2\,, \tan^2\theta = 0.39^{+0.05}_{-0.04}\,. \quad (2)$$

These results are in agreement with those reported in the several state-of-the-art analysis of solar and KamLAND data which exist in the literature.

Atmospheric and K2K Neutrinos

In Fig. 2 I show the results of our latest analysis of the ATM neutrino data [9], which includes the full data set of Super-Kamiokande phase I (SK1) as well as:

- use of new three-dimensional fluxes from Honda;
- improved interaction cross sections;
- some improvements in the Monte-Carlo which lead to some changes in the actual values of the data points.

Our results show good quantitative agreement with those of the SK collaboration. In particular we find that after inclusion of the above effects, the allowed region is shifted to lower Δm^2 with best-fit point and 1σ ranges:

$$\Delta m^2 = \left[2.2^{+0.6}_{-0.4}\right]\times 10^{-3}\ \mathrm{eV}^2\,, \qquad \tan^2\theta = 1^{+0.35}_{-0.26}\,. \quad (3)$$

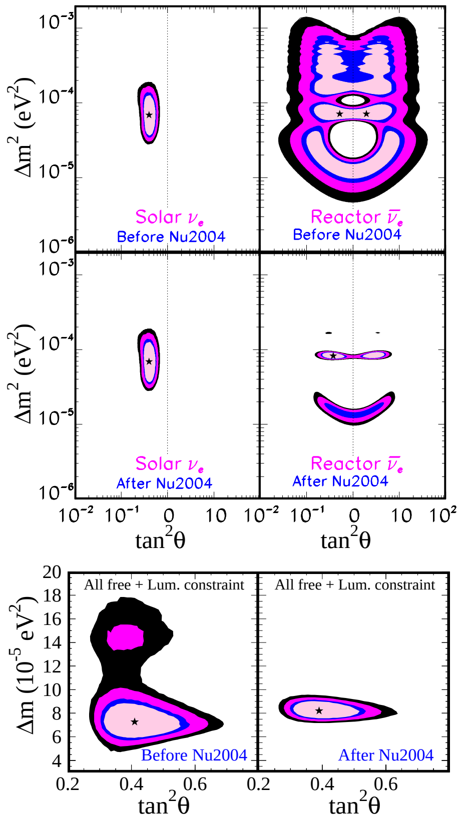

FIG. 1: Allowed regions for 2-ν oscillations of solar ν_e and KamLAND $\bar{\nu}_e$ (upper four panels), and for the combination of KamLAND and solar data under the hypothesis of CPT conservation (lower two panels). The different contours correspond to the allowed regions at 90%, 95%, 99% and 3σ CL.

At this point I would like to raise a word of caution. In all present analysis of ATM data, two main sources of theoretical flux uncertainties are included: an energy independent normalization error and a "tilt" error which parametrizes the uncertainty in the $E^{-\gamma}$ dependence of the flux. Some additional uncertainties in the ratios of the samples at different energies are also allowed as well as uncertainties in the zenith dependences. However, we still lack a well established range of theoretical flux uncertainties within a given ATM flux calculation, in a similar fashion to what it is provided for the solar neutrino fluxes by the SSM. In the absence of these, we cannot be sure that we are accounting for the most general characterization of the energy dependence of the ATM neutrino flux uncertainties. Given the large amount of data points provided by the SK experiment, this is becoming an important issue in the ATM neutrino analysis. There is a chance that the ATM fluxes may be still too "rigid", even when allowed to change within the presently considered uncertainties. As a consequence, we may be overconstraining the oscillation parameters.

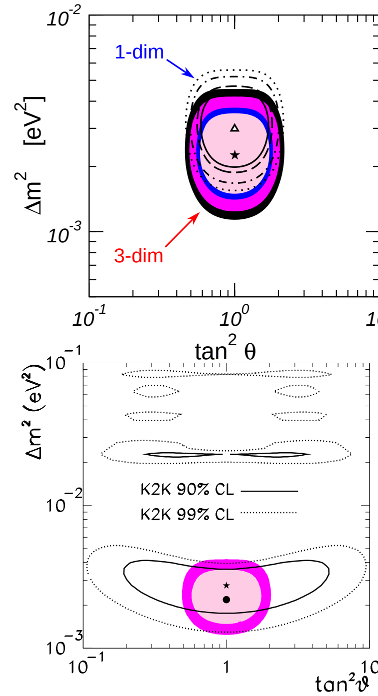

FIG. 2: *Upper*: Allowed regions from the analysis of ATM data using the new (full regions labeled "3-dim") and old (empty curves labeled as "1-dim") SK1 data and ATM fluxes. The different contours correspond to at 90%, 95%, 99% and 3σ CL. *Lower*: Allowed regions from the analysis of K2K data at 90% (full line) and 99% (dashed line) confidence level. For comparison we also show the corresponding allowed regions from ATM neutrinos at the same CL.

The evidence of oscillation of ATM ν_μ has been now confirmed by the long-baseline (LBL) K2K experiment which has observed not only a deficit of ν_μ's at a distance of 250 km but it has also measured the distortion of their energy spectrum. In the lower panel of Fig. 2 I show the results of our preliminary analysis of the K2K data which graphically illustrates this agreement.

Three-Neutrino Oscillations

The minimum joint description of ATM, K2K, solar and reactor data requires that all the three known neutrinos take part in the oscillations. The mixing parameters are encoded in the 3×3 lepton mixing matrix which can be conveniently parametrized in the standard form $U =$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$. The angles θ_{ij} can be taken without loss of generality to lie in the first quadrant, $\theta_{ij} \in [0, \pi/2]$.

There are two possible mass orderings, which we denote as *Normal* and *Inverted*. In the normal scheme

$m_1 < m_2 < m_3$ while in the inverted one $m_3 < m_1 < m_2$.

In total the 3-ν oscillation analysis involves seven parameters: 2 mass differences, 3 mixing angles, the CP phase and the mass ordering. Generic 3-ν oscillation effects include:

– coupled oscillations with two different wavelengths;

– CP violating effects;

– difference between Normal and Inverted schemes.

The strength of these effects is controlled by the values of the ratio of mass differences $\alpha \equiv \Delta m^2_{21}/|\Delta m^2_{31}|$, by the mixing angle θ_{13} and by the CP phase δ.

For solar and ATM oscillations,

$$\Delta m^2_{\odot} = \Delta m^2_{21} \ll |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| = \Delta m^2_{\rm atm}. \tag{4}$$

and the joint 3-ν analysis simplifies as follows:

– for solar and KamLAND neutrinos, the oscillations with the ATM oscillation length are completely averaged and the survival probability takes the form:

$$P^{3\nu}_{ee} = \sin^4\theta_{13} + \cos^4\theta_{13} P^{2\nu}_{ee} \tag{5}$$

where in the Sun $P^{2\nu}_{ee}$ is obtained with the modified sun density $N_e \to \cos^2\theta_{13} N_e$. So the analyses of solar data constrain three of the seven parameters: $\Delta m^2_{21}, \theta_{12}$ and θ_{13}. The effect of θ_{13} is to decrease the energy dependence of the survival probability;

– for ATM and K2K neutrinos, the solar wavelength is too long and the corresponding oscillating phase is negligible. As a consequence, the ATM data analysis restricts $\Delta m^2_{31} \simeq \Delta m^2_{32}$, θ_{23} and θ_{13}, the latter being the only parameter common to both solar and ATM neutrino oscillations and which may potentially allow for some mutual influence. The effect of θ_{13} is to add a $\nu_\mu \to \nu_e$ contribution to the ATM oscillations;

– at CHOOZ the solar wavelength is unobservable and the relevant survival probability oscillates with wavelength determined by Δm^2_{31} and amplitude determined by θ_{13}.

In this approximation, the CP phase is unobservable. In principle there is a dependence on the Normal versus Inverted orderings due to matter effects in the Earth for ATM neutrinos. However, this effect is controlled by the mixing angle θ_{13}. Presently all data favour small θ_{13} with best fit point very near $\theta_{13} = 0$. The dominant constraint arises from the combined analysis of CHOOZ reactor and ATM data and it is further limited by the solar and KamLAND results. As a consequence, this effect is too small to be statistically meaningful in the present analysis.

In Fig. 3 I show the individual bounds on each of the five parameters derived from the global analysis. To illustrate the effect of the new KamLAND and K2K data we also show the results before their inclusion. In each panel the displayed $\Delta\chi^2$ has been marginalized with respect to the undisplayed parameters. As seen in the figure the main effect of the new data is a better determination of

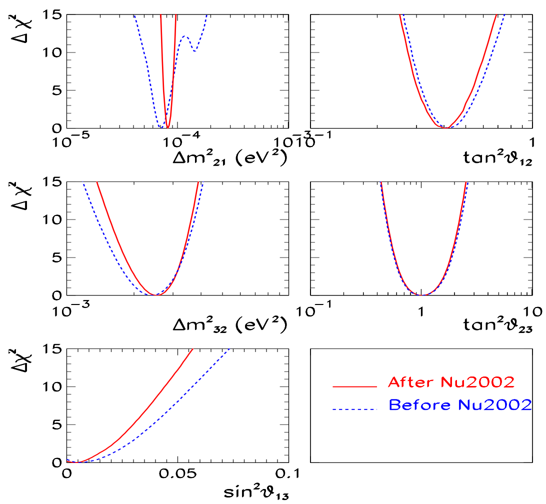

FIG. 3: Global 3ν oscillation analysis. Each panel on the left shows the dependence of $\Delta\chi^2$ on each of the five parameters from the global analysis compared to the bound prior to the inclusion of the new KamLAND and K2K data.

the mass differences. A secondary effect is the slight improvement of upper bound on θ_{13}. This is mainly driven by K2K which favours the higher mass part of the ATM neutrino region for which the corresponding bound from CHOOZ is tighter.

Altogether we find the following 3σ ranges:

$$\begin{aligned} 7.3 \le \frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2} \le 9.3 \qquad & 0.28 \le \tan^2\theta_{12} \le 0.60\,, \\ 1.6 \le \frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2} \le 3.6\,, \qquad & 0.5 \le \tan^2\theta_{23} \le 2.1\,, \\ & \sin^2\theta_{13} \le 0.041\,. \end{aligned} \tag{6}$$

These results can be translated into our present knowledge of the moduli of the mixing matrix U:

$$|U| = \begin{pmatrix} 0.79-0.88 & 0.47-0.61 & <0.20 \\ 0.19-0.52 & 0.42-0.73 & 0.58-0.82 \\ 0.20-0.53 & 0.44-0.74 & 0.56-0.81 \end{pmatrix}. \tag{7}$$

To finish this section I would like to discuss the possible observability of Δm^2_{21} oscillations in ATM neutrinos. These effects although small can, in principle be visible, mostly in the low energy ν_e events provided that the mixing angle θ_{23} deviates from maximal (see Ref. [10] and references in therein). As a matter of fact, they can lead to an increase or a decrease of the sub-GeV e-like events depending on the octant of the angle θ_{23} and they can be our best observable to detect both deviations of θ_{23} from maximal as well as the sign of the deviation.

The present data may already give some hint of deviation of the 2-3 mixing from maximal. Indeed, there is some excess of the $e-$like events in the sub-GeV range. The excess increases with decrease of energy within the

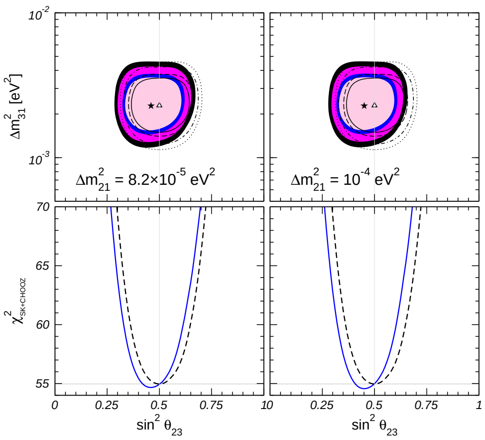

FIG. 4: Effect of Δm^2_{21} oscillations on the allowed regions of the oscillation parameters Δm^2_{31} and $\sin^2\theta_{23}$ from the combined analysis of all the ATM and CHOOZ data samples. In the lower panels we show the dependence of the χ^2 function on θ_{23}, marginalized with respect to Δm^2_{31}. Hollow and dashed black lines are for $\Delta m^2_{21} = 0$.

sample as expected from a Δm^2_{21} effect. To illustrate this I show in Fig. 4 the results of the global analysis of ATM and CHOOZ data in the framework of 3ν oscillations taking into account also the effect of Δm^2_{21} oscillations [10].

From the figure we see that, even with the present uncertainties, the ATM data has some sensitivity to Δm^2_{21} oscillation effects and that these effects break the symmetry in θ_{23} around maximal mixing. Although statistically not very significant, this preference for non-maximal 2-3 mixing is a physical effect on the present neutrino data, induced by the fact than an excess of events is observed in sub-GeV electrons but not in sub-GeV muons nor, in the same amount, in the multi-GeV electrons. As a consequence, this excess cannot be fully explained by a combination of a global rescaling and a "tilt", of the fluxes within the assumed uncertainties.

UNORTHODOX FITS

I denote by *Unorthodox* fits those in which either the matter contents of the SM has been extended to include new light sterile neutrinos or the basic symmetries of the model are violated, in most cases with the aim of accommodating the LSND signal.

LSND and Sterile Neutrinos

The LSND experiment found evidence of $\overline{\nu}_\mu \to \overline{\nu}_e$ neutrino conversion with $\Delta m^2 \geq 0.1$ eV^2. This result can be accommodated together with those from solar, reactor, ATM and LBL experiments into a single neutrino oscillation framework only if there are at least three different

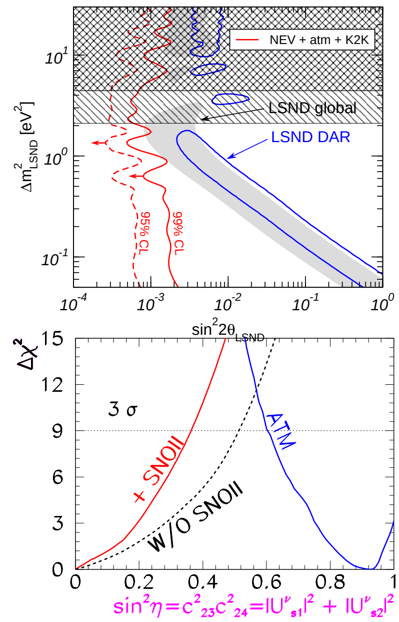

FIG. 5: *Upper*: Status of the 3+1 oscillation scenarios. *Lower*: Present status of the bounds on the active-sterile admixture from solar and ATM neutrino data in (2+2)-models.

scales of neutrino mass-squared differences.

As a first attempt to generate the required scales one can invoke the existence of a fourth light neutrino, which must be *sterile* in order not to affect the invisible Z^0 decay width, precisely measured at LEP. There are six possible four-neutrino schemes which, in principle, can do the job. They can be divided in two classes: (3+1) and (2+2). In the (3+1) schemes, there is a group of three close-by neutrino masses that is separated from the fourth one by a gap of the order of 1 eV^2, which is responsible for the SBL oscillations observed in the LSND experiment. In (2+2) schemes, there are two pairs of close masses separated by the LSND gap. The main difference between these two classes is that in (2+2)-spectra the transition into the sterile neutrino is a solution of either the solar or the ATM neutrino problem, or the sterile neutrino takes part in both. This is not the case for a (3+1)-spectrum, where the sterile neutrino could be only slightly mixed with the active ones and mainly provide a description of the LSND result.

I show in Fig. 5 the latest results of the analysis of neutrino data in these scenarios. The phenomenological situation at present is that none of the four-neutrino scenarios are favored by the data. (3+1)-spectra are disfavored by the incompatibility between the LSND signal and the negative results found by other short-baseline (SBL) laboratory experiments. There is also a constraint on the possible value of the heavier neutrino mass in this scenario from their contribution to the energy density in the Universe which is presently constrained by cosmic microwave background radiation and large scale structure

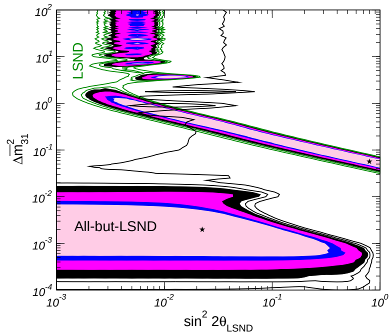

FIG. 6: 90%, 95%, 99%, and 3σ CL allowed regions (filled) in required to explain the LSND signal together with the corresponding allowed regions from our global analysis of all-but-LSND data. The contour lines correspond to $\Delta\chi^2 = 13$ and 16 (3.2σ and 3.6σ, respectively).

formation data [6]. This is illustrated in the upper panel of Fig. 5 taken from Ref. [11] where they find that after the inclusion of the cosmological bound there is only a marginal overlap at 99% CL between the allowed LSND region and the excluded region from SBL+ATM experiments. Concerning (2+2)-spectra, they are ruled out by the existing constraints from the sterile oscillations in solar and ATM data as illustrated in the lower panel which shows that the lower bound on the sterile component from the analysis of ATM data and the upper bound from the analysis of solar data do not overlap at more than 4σ.

Neutrinos as Tests of Fundamental Symmetries

Alternative explanations to the LSND result include the possibility of CPT [12] violation, which implies that the masses and mixing angles of neutrinos may be different from those of antineutrinos. To test this possibility, in Ref. [13] we performed an analysis of the existing data from solar, ATM, LBL, reactor and SBL experiments in the framework of CPT violating oscillations. The outcome of the analysis is that, presently, the hypothesis of CPT violation is not supported by the data. This arises from two main facts: (i) KamLand finds that reactor $\overline{\nu}_e$ oscillate with wavelength and amplitude in good agreement with the expectations from the LMA solution of the solar ν_e; (ii) both ATM neutrinos and antineutrinos have to oscillate with similar wavelengths and amplitudes to explain the ATM data. In general, as a result of these effects, the best fit to the data is very near CPT conservation and in particular this rules out this scenario as explanation of the LSND anomaly. This is illustrated in Fig. 6, which shows clearly that there is no overlap below the 3σ level between the LSND and the all-but-LSND allowed regions.

Using the good description of neutrino data in terms of neutrino matter oscillations, it is also possible to constraint other exotic forms of new physics such as the violation of Lorentz Invariance (VLI) [14] induced by different asymptotic values of the velocity of the neutrinos, $c_1 \neq c_2$, or the violation of the equivalence principle (VEP) [15] due to non universal coupling of the neutrinos, $\gamma_1 \neq \gamma_2$ to the local gravitational potential, among others. These forms of new physics, if non-universal, can also induce neutrino flavour oscillations whose main differentiating characteristic is a different energy dependence of the oscillation wavelength. For example for both VLI and VEP the oscillation wavelength decreases with energy unlike for mass oscillations. ATM neutrino events extend over several decades in energy. As a consequence they can test the presence of this effect even at the subdominant level. In Ref. [9] we have performed an analysis of ATM and LBL neutrino data in terms of neutrino mass oscillations plus these new physics effects and we have concluded that the determination of mass and mixing parameters is robust under the presence of these unknown forms of new physics. Conversely, the analysis permits to impose strong constraints on the violations of these symmetries. For instance we find that at 90% CL the possible VLI a and VEP are limited to

$$\frac{|\Delta c|}{c} \leq 8.1 \times 10^{-25} \, , \qquad |\phi \, \Delta\gamma| \leq 4.0 \times 10^{-25} \, . \quad (8)$$

which constitute the strongest constraints on the violation of these fundamental symmetries.

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